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EFFECT OF MAGNET ERRORS ON SLOW EXTRACTION

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Summary

calculate analytically the expected tune shifts systematic sextupole and decapole errors in the design of reference design A at an energy of 1.86 TeV. The momentum-dependent tune shift due to sextupole errors is $\Delta\nu_x = -0.0557$ for $\Delta p/p = \pm 2 \times 10^{-3}$. The sextupole component in the SSC dipoles Δb_2 is less than 5×10^{-4} .

Introduction

Systematic errors in the SSC magnets define the "aperture" for the fixed-target option. During extraction the amplitude growth of the resonant oscillations is generated by nonlinear fields. Sextupoles are utilized for 1/3-integer resonance. The field distortions present in the sextupoles and quadrupoles can perturb or suppress the growth of the oscillations.

Systematic errors generate amplitude- and energy-dependent tune shifts; during the extraction these effects can cause (1) a reduction in step 1 extraction efficiency, (2) curving of the beam, (3) possibly retrapping, and (4) emittance growth. Random errors due to errors in coil placement, for example, interfere with the extraction harmonics. Random horizontal fields near the coils and random vertical fields near the coils can increase the vertical emittance and the extraction process.

In this short note we estimate analytically the tune shifts caused by the multipoles in the SSC dipoles of reference design A. We restrict the analysis to the systematic sextupole and decapole errors and sextupole errors. The machine energy is taken to be 1.86 TeV. Then from pp. 184-187 of the reference study¹ (RNS) we use for the systematic errors $\Delta b_2 = 1.6 \times 10^{-4} \text{ cm}^{-2}$, $b_4 = 2.52 \times 10^{-4} \text{ cm}^{-4}$, and the random sextupole $\Delta b_2 = 1.6 \times 10^{-4} \text{ cm}^{-2}$.

Tune Shifts Due to Systematic Errors

Tune shifts due to systematic errors were also calculated analytically for the SPS.² Approximate formulas were developed that include only averaged quadratic expressions require no tracking or integration around the machine. Four formulas for the tune shifts can be written

$$\Delta\nu_x = -\frac{3\nu}{12R^2} \frac{\langle \beta^{3/2} \rangle}{\beta_{\text{max}}} \left(\frac{a}{A^2}\right)^2 (b_2 A^2)^2, \quad (1)$$

$$\Delta\nu_x = -\frac{\nu}{A^2 \gamma_c^2} \frac{\langle \beta^{3/2} \rangle}{\langle \beta^{1/2} \rangle} b_2 A^2 \frac{\Delta p}{p}, \quad (2)$$

$$\Delta\nu_x = -\frac{2\nu}{R} \frac{\langle \beta^{7/2} \rangle}{\langle \beta^{1/2} \rangle^3} \left(\frac{R}{\gamma_c}\right)^3 \frac{b_4 A^4}{A^4}, \quad (3)$$

$$\Delta\nu_x = -\frac{3\nu}{2\beta_{\text{max}} \gamma_c^2} \frac{\langle \beta^{7/2} \rangle}{\langle \beta^{1/2} \rangle} \frac{\Delta p}{p} \left(\frac{a}{A^2}\right)^2 b_4 A^4. \quad (4)$$

In Eqs. (1)-(4) ν is the horizontal betatron tune (we assume $\nu = 97^{1/3}$), R is the machine radius ($R = 14.324 \text{ km}$), a is the amplitude of the betatron oscillation of the particle measured at $\beta = \beta_{\text{max}}$, A is the aperture of the magnet, and $\Delta p/p$ is the relative deviation of the particle momentum from the nominal value. The averaging of the listed powers of beta was accomplished by averaging over the standard 200-m FODO cells.¹ We obtain $\langle \beta^{1/2} \rangle = 11.8 \text{ m}^{1/2}$, $\langle \beta^{3/2} \rangle = 378 \times 10^3 \text{ m}^{3/2}$, and $\langle \beta^{7/2} \rangle = 85.3 \times 10^6 \text{ m}^{7/2}$.

Equation (1) is the amplitude-dependent tune shift due to sextupole errors and Eq. (2) is the nonlinear momentum-dependent tune shift. Equations (3) and (4) represent the tune shifts due to decapole errors--in the former case the shift is just due to $\Delta p/p$ effects; for the latter the tune shift arises from combined $\Delta p/p$ and amplitude dependence. The nonlinear equations used to obtain Eqs. (1)-(4) are solved in Landau and Lifshits.³

Equations (1)-(4) were evaluated assuming the SSC aperture $A = 10 \text{ mm}$, $\gamma_c = 88.35$, $\beta_{\text{max}} = 332 \text{ m}$, and $a = 5 \text{ mm}$. We obtain $\Delta\nu_1 = -0.001$, $\Delta\nu_2 = -0.0557$, $\Delta\nu_3 = -2 \times 10^{-7}$, and $\Delta\nu_4 = -0.0011$. For resonant extraction the $\Delta\nu_2$ term will be fatal if the b_2 multipole is not corrected by at least a factor of ~ 20 . The stopband width around $\nu = 97^{1/3}$ should be near ± 0.003 .

Effects Due to Random Errors

Random sextupole fields in the bending magnets can give rise to a sextupole component with, for example, a 292nd harmonic that interferes with the 292nd harmonic generated intentionally for extraction at $\nu = 97^{1/3}$. The harmonic is given by⁴

$$B_{\text{rda}} = -\frac{1}{\beta_{\text{sep}}^{1/2} B_p} \oint \frac{B_0}{A^2} \frac{\Delta B}{B} \beta^{3/2} \cos(292\phi) ds, \quad (5)$$

where B_0 is the dipole field (6.5 T), $\Delta B/B$ is the fractional error field at the aperture A , $\phi = ds/(vB)$, and β_{sep} is beta at the slow-extraction septum. For random errors we write

$$B_{\text{rda}} = -\frac{B_0}{\beta_{\text{sep}}^{1/2} B_p A^2} \left\{ \sum [I_d \beta^{3/2} \cos(292\phi)]^2 \right\}^{1/2} \left\langle \frac{\Delta B}{B} \right\rangle. \quad (6)$$

To simplify matters we assume $\beta^{3/2}$ is constant over the 3870 SSC dipoles, $A = 10 \text{ mm}$, $I_d = 16.6 \text{ A}$, and $\beta_{\text{sep}} = 1500 \text{ m}$ in the center of a utility straight section. We

arbitrarily choose S_{rdm} to amount to no more than 25% of the harmonic generated by the extraction sextupoles, which we have calculated to be $S_h = 133.3 \text{ m}^{-1}$. This condition then requires [from Eq. (6)] that $\langle \Delta B/B \rangle < 5.0 \times 10^{-4}$. The SSC dipoles do satisfy this requirement.

Conclusions

Based on the above analysis it appears that slow resonant extraction can proceed with a "good field aperture" of 1-cm radius in the SSC, providing that the systematic sextupoles for the dipoles (b_2 as listed on p. 184 in Ref. 1) can be reduced by at least a factor of 20.

References

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